

FINAL REPORT

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BLADE FLUTTER IN COMPRESSORS AND FANS--  
NUMERICAL SIMULATION OF THE AERODYNAMIC LOADING

BY

DAVID M. KUZC  
EDWIN E. YEAKEL  
SAMIR F. RADWAN  
STANLEY H. JOHNSON  
DONALD O. ROCKWELL

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DEPARTMENT OF MECHANICAL ENGINEERING AND MECHANICS  
LEHIGH UNIVERSITY  
BETHLEHEM, PENNSYLVANIA



INTRODUCTION

This report covers work in three areas related to the flutter of blades on a single bladed-disk assembly in the fan or compressor section of aircraft engines: (1) the development of a numerical algorithm for the simulation of the unsteady flow field resulting from flutter in an infinite two-dimensional cascade of flat plates, (2) the determination of the ability of simple linear models to accurately represent the effects of blade mistuning on the harmonic responses, both free and forced, of a bladed-disk assembly, and (3) a critical review of the existing interpretations of the trailing-edge condition, addressing both theoretical and experimental works in steady, as well as unsteady flows.

The complete final report consists mainly of the MS theses submitted on a timely basis during the life of the contract: (1) "The Simulation of Unsteady

Aerodynamics using the Numerical Method of Lines", by David M. Kuzo, (2) "A Simple Model for the Study of the effects of of Mistuning on Blade Vibrations in Axial-Flow Turbomachines", by Edwin E. Yeakel, and (3) "Critical Review of the Trailing Edge Condition in Steady and Unsteady Flow", by Samir F. Radwan.

#### THESIS BY KUZO

The Kuzo thesis describes the development of a numerical algorithm for the simulation of the unsteady flow field resulting from flutter in an infinite two-dimensional cascade of flat plates. The Numerical Method of Lines is used in conjunction with a time-advancing integrator for the simulation.

The numerical model of the flow field is developed using a finite isolated airfoil in a nonconvecting fluid. A performance assessment is made of the numerical integration parameters. Optimum parameters are then used to compute trial solutions for finite isolated and cascaded airfoils in a convecting fluid. Computed airfoil loading curves for incompressible flow are examined in light of Theodorsen's potential solution for an unsteady isolated flat plate.

The previous numerical models of Ni [43,44]<sup>1</sup> and Beam and Warming [41,42] are assessed in the Kuzo report. It is found that Ni's formulation overspecifies the problem by requiring as input the airfoil vorticity distribution. The formulation of Ni also uses a spatial smoothing algorithm to aid convergence that is found to severely decrease accuracy. The numerical

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<sup>1</sup>Numbers in square brackets refer to references in the thesis under discussion.

algorithm of Beam and Warming is found to be acceptable.

Lacking in the above works is a careful consideration of the trailing edge and wake flows<sup>2</sup>. It is expected that careful attention to these regions will yield significant changes in the calculated values of airfoil lift.

The flow is modeled as compressible, inviscid and isentropic flow. The velocity and density fields are obtained by solving the Euler and continuity equations in conservative form.

The goal of this work was to establish an efficient computational procedure that requires only the prescribed airfoil motion as input. The algorithm should also allow the analyst to separate the numerical formulation from the physics of the flow model. this allows greater attention to be given to the modeling of critical flow regions at the trailing edge and wake.

From the presented results it is clear that the success of Kuzo's procedure is dependent upon the variable-step integrator error limit and the viscosity coefficient. there is a necessary trade-off between solution accuracy and convergence rate. The largest discrepancy results from applying an artificial viscosity algorithm to a problem containing large field-property gradients, as in cascade flutter.

The procedure is superior to that of Ni in that the only required blade motion input is the perturbation velocity. The biased spatial-derivative

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<sup>2</sup>This motivated the critical survey by Radwan to be described below. A preliminary examination of the questions is included in the Kuzo thesis.

algorithm capability of the Numerical Method of Lines allows for a better handling of flow discontinuities, solid boundaries and shock waves. Unlike the works of Ni and Beam and Warming, Kuzo reviewed the fluid dynamic conditions that are important for the modeling of unsteady flow.

More development of the Kuzo procedure is required before flutter calculations can be made. The following improvements are recommended:

1. adaption of the artificial viscosity algorithm to account for the variable stepsize of the integrator
2. coordinate stretching along the airfoil leading and trailing edges to better resolve the flow properties there
3. decrease the execution time by choosing a starting condition for the flow field properties from previously established results.

#### THESIS BY RADWAN

Early progress in predicting aerodynamic forces on bodies in incompressible flow involved potential flow analysis. In such analyses, the Kutta-Joukowski condition [1902,1906] is used to permit a unique solution for both isolated airfoils and airfoils in cascade. This mathematical condition requires that the flow velocity at a sharp trailing edge be finite. The resultant flow pattern and the predicted lift agree well with that observed at low angles of attack. However many other interpretations have been used which can lead to serious discrepancies in predictions of aerodynamic forces and moments. A critical review of these various interpretations is presented by Radwan.

Radwan begins with various interpretations of the Kutta-Joukowski condition. However this condition is violated when the trailing edge is not

sharp, even though the flow is steady. In this case, the trailing-edge region is dominated by viscous effects. For this class of trailing edges the Taylor-Howarth criterion of "zero total flux of vorticity into the wake" is found to be the appropriate edge condition for steady flow to establish the circulation and the aerodynamic forces. Details are given on the nature of the trailing-edge flow structure emphasizing the role of viscosity in smoothing the flow field in laminar nonseparated flow using the multistructured boundary layer theory of Stewartson.

The complexity of the problem increases when airfoils with rounded trailing edges operate under unsteady conditions. In such cases there are all of the previously encountered difficulties of steady flow plus the unsteady effects on the boundary layer and the vorticity eventually shed from the trailing edge. These effects give rise to significant trailing-edge loading and strong acoustic radiation from the trailing edge when separation occurs. A critical review of the problem, especially the unsteady aspects, is the main content of Radwan's report.

Radwan concludes that, for cases where the airfoil has a sharp trailing edge, there is no disagreement that the Kutta-Joukowski condition is to be satisfied. All interpretations discussed therein are essentially identical and give good agreement with experimental results. For most isolated airfoils or blade cascades having blunt trailing edges the Kutta-Joukowski condition has no relevance. For this class of trailing edges the Taylor-Howarth criterion is found to be the appropriate trailing-edge condition and unique flow solutions can be produced.

For unsteady analysis the situation is more complicated. However, it has

been shown that the trailing-edge condition of "zero pressure loading" is the appropriate condition as long as the flow remains attached and the reduced frequency is low. In such cases the acoustic radiation field is very weak. Unfortunately, investigators have pointed out many cases which violate these conditions, i.e., when the flow separates and the unsteadiness is high and accompanied by strong acoustic radiation from the trailing edge. Radwan concludes that further efforts in this area are called for and recommends:

1. further experimental studies covering a range of reduced frequencies and angles of attack to guide new theoretical analyses
2. the multistructure boundary-layer theory should be extended, if possible, to gain an understanding of the trailing-edge structure when the flow separates
3. critical testing of these new approaches would be needed to define the limits of their applicability.

#### THESIS BY YEAKEL

The purpose of this work is to develop a simplified model for the simulation of the vibration characteristics of a bladed-disk assembly in a compressor stage of a turbofan engine. The emphasis is on mistuning (also referred to as detuning). The term mistuning refers to the nonuniformities which exist between individual blades mounted on the same disk. These nonuniformities involve differences in blade stiffness and/or mass which result from normal manufacturing tolerances. An investigation is made of the effects of mistuning on the vibration characteristics of a bladed-disk assembly.

Several different types of models for the analysis of turbofan blade vibration have been proposed in the literature, having varying degrees of

accuracy. Most of these are some variation of a discretized mass - spring - dashpot arrangement [3,4]. Reference [5] proposes this type of analysis to simulate the blades in combination with a Myklestad approach, the purpose of which is to simulate disk flexure. Still another method [6] has been to treat the disk as a circular plate of uniform thickness and each blade as a cantilevered beam. Blade and disk influence coefficients are calculated leading to a matrix formulation of the problem. Finally, with the advent of powerful finite-element routines the finite-element method has also seen application in the field [7,8].

The model developed by Yeakel is of the lumped-parameter type utilizing discrete masses and linear elastic springs to represent individual blade masses and stiffnesses and interblade coupling effects. It is not meant to be a finalized version for field use, rather it is meant to serve as an heuristic tool for the understanding of blade flutter.

In this so-called "trolley model" each blade is discretized as a discrete mass with one degree of freedom coupled to a stationary foundation, i.e., the disk, by a linear elastic spring with linear elastic coupling between adjacent blades. In this manner the bending vibrations of the blades and interblade coupling are represented. This coupling may be attributed to aerodynamic effects or mechanical coupling through the disk. Natural frequencies, mode shapes and responses to harmonic excitation are computed.

The major downfall of this analysis is the omission of coupling effects between nonadjacent blades. These effects arise from larger scale deflections of the disk on which the blades are mounted. However, these effects are frequency dependent and difficult to portray. Also, the argument can be made

that for high frequencies the disk becomes sufficiently stiff that it undergoes little or no deflection. Some of the factors in favor of the "trolley model" are:

1. The model exhibits good qualitative agreement with experiment results published by Ewins [6] for the higher modes of vibration. That is, the computed mode shapes are in good agreement with those those obtained experimentally. With some manipulation, quantitative agreement to within less than one percent can also be obtained. This tends to support the supposition that the disc becomes stiffer at high frequencies.
2. One of the main reasons for studying blade vibration is the problem of fatigue failure in the blades. These failures are caused by cyclic bending loads acting at the root of the blade resulting from bending vibration. Blade bending is more serious at higher frequencies. At lower frequencies the vibratory motion is predominantly disc deflection. As stated earlier, the former case is the one for which the model works best.
3. Some of the work done by others deals with the aerodynamic effects between two vibrating blades. In such a case it would not necessarily be useful to study vibration modes which consist mostly of disc deflection. These studies involve the airflow between two adjacent blades and therefore are not concerned with disc movements.<sup>3</sup>
4. Due to the model's simplicity the simulation can be accomplished with a relatively small amount of computational effort. The model can be expanded readily without becoming computationally unmanageable.

The model exhibits the kind of behavior found in the literature for mistuned systems. These phenomena include complex amplitude distributions, typified by vibration confined to small groups of blades, and increased susceptibility to certain types of excitation. In a tuned system the mode shapes have distinct nodal diameter patterns in which amplitudes vary sinusoidally or cosinusoidally around the circumference of the system. If the

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<sup>3</sup>Refers to the work of Kuzo



forcing function is of the engine-order type, resonant behavior will occur only in the case where the number of nodal diameters equals the number of engine orders for the forcing function. However, in a mistuned system the mode shapes do not exhibit this regular amplitude distribution. Each mode shape can be treated as a superposition of nodal diameter mode shapes. Therefore, each mode which contains a nodal diameter component of the same order as the forcing function engine order will be excited if the forcing frequency equals the natural frequency of that particular mode. Thus, where in the case of the tuned system only one resonance was excited, any number of resonances can be excited in a mistuned system. Also, in a tuned system the natural modes occur in pairs having the same natural frequencies and similar mode shapes. It has been shown that in a mistuned system these pairs split into two distinct modes having slightly different natural frequencies. In effect the number of potential resonant frequencies is doubled.

There are several ways in which the model can be either expanded or improved. One possibility is the inclusion of more aerodynamic damping (both positive and negative) . This would involve the addition of a dashpot between adjacent blades and would, of course, make necessary some other method for solving the eigenvalue problem. Some of the simulation of single-channel fluid dynamic phenomena could perhaps be useful in determining the appropriate damping constants. Another possibility would be to further discretize the system in order to take into account modes of vibration involving "second bending" blade vibrations.

#### SUMMARY

This report marks the completion of work under NASA Research Grant

NSG3162 and the beginning of a joint research program between the Lehigh University Department of Mechanical Engineering and Mechanics and the NASA Lewis Research Center Airbreathing Engines Division in the area of blade flutter in compressors and fans. This first project was devoted to establishing frequent interaction on a broad front while simultaneously pursuing a specific problem in the numerical simulation of subsonic flutter in an infinite two-dimensional cascade of flat plates by the Numerical Method of Lines. The results of the two-dimensional simulations are reported above and no similar work is presently underway nor contemplated. However, other areas of inquiry have been begun, the initial phases of which are described above, which continue. These include the investigation of the effects of mistuning and the simulation of a mistuned rotor. Other work has begun on the potential of internal acoustic reflections as a cause of some types of observed flutter phenomena.